2010

Design of a conventional submarines with advanced air independent propulsion systems and determination of corresponding theater-level impacts

Design of Conventional Submarines with Advanced Air Independent Propulsion Systems and Determination of Corresponding Theater-Level Impacts

Konstantinos Psallidas, Clifford A. Whitcomb, and John C. Hootman

Abstract

Finding a quiet, state-of-the-art conventional submarine in a large area is a challenging task and the potential impacts of the threat of such a submarine can delay operations and consume large numbers of military assets. At the theater level, a technological impact assessment of the operational characteristics of a notional air independent propulsion (AIP) system submarine design is performed using a mission simulation context. This paper refreshes the topic of conventional submarine design, provides examples of analyses that demonstrate the assessment of the performance characteristics of current technology, and provides aids for decision makers in determining the impacts of future designs and possible threats. At the theater level, a technological impact assessment of the operational characteristics of a notional AIP system submarine design is performed using a mission simulation context. This study investigates potential improvements by varying systems within the same hull form. The results demonstrate the probability of detections possible with AIP propulsion systems.

Introduction

Finding a quiet, state-of-the-art conventional submarine in a large area is a challenging task and the potential impacts of the threat of such a submarine can delay operations and consume large numbers of military assets (Challenge of ASW in the Littorals, The Surface Warfare 2002). As operations at sea are moving from the "blue water" open ocean to the "brown water" littoral environment, the importance of small conventional submarines is increasing. During Congressional testimony in 1997, RADM Michael W. Cramer, former Director of Naval Intelligence, stressed that "the proliferation of submarine technology is the most significant submarine challenge facing the US Navy as we approach the 21st Century" (Cramer 1997).

At the theater level, a technological impact assessment of the operational characteristics of a notional air independent propulsion (AIP) system submarine design is performed using a mission simulation context. This paper refreshes the topic of conventional submarine design, provides examples of analyses that demonstrate the assessment of performance characteristics of current technology, and aids decision makers in determining the impacts of future designs and possible threats.

Background

ROLE OF CONVENTIONAL SUBMARINES

Following the end of the Cold War, there have been significant changes in the nature of naval missions. The focus of undersea warfare has

Nomenclature

AC: Alternating current

AIP: Air independent propulsion

ASW: Antisubmarine warfare

***b*:** Constants of regression

B: Buoyancy

CCD: Closed cycle diesel

DC: Direct current

DCN: Direction des Construction Navales

DE: Diesel electric

DOE: Design of experiments

DSRV: Deep submergence rescue vehicle

e: Error term

ft: Feet

HDW: Howaldtswerke-Deutsche Werft GmbH

PEMFC: Proton exchange membrane fuel cells

IR: Indiscretion rate/ratio

***m*:** RSE factors

kW: Kilowatt

LAIS: Lithium–aluminum/iron sulfide

MESMA: Module Energie Sous-Marin Autonome

MOE: Measure of effectiveness

***n*:** Number of RSM dimensions

nm: Nautical mile

OMOE: Overall MOE

***p*:** DOE factors

P_{detect}: Probability of detection

PDS: Positive detection swath

R&D: Research and development

RSE: Response surface equation

DOI: 10.1111/j.1559-3584.2010.00196.x

RSM: Response surface method

SOA: Speeds of advance

TNSW: Thyssen Nordseewerke GmbH

$t_{snorkeling}$: Time submarine spends snorkeling

t_{quiet}: Time submarine spends on battery or AIP

v: Volume

V: Volume

w: Weight

shifted from traditional "blue water" missions to littoral operations. This new strategic environment is a key driver in shaping future naval vessels.

Powerful nuclear submarines with unlimited underwater endurance are well suited to the task of sea control in the open ocean, and are able to transit at high speeds while submerged to a distant patrol area or escort surface shipping. However, a modern submarine's role in littoral warfare is likely to be one of access denial to opposing forces. While this is not a new mission, small, conventionally powered submarines remain suitable for littoral operations because of their low acoustic, magnetic, and thermal signatures. Highly capable conventional submarines now form a key part of more than 66 nations' order of battle (Whitcomb and McHugh 1999).

The Falklands Conflict of 1982 can be used to illustrate the impact a conventional submarine can have in littoral operations. At the time of the conflict, the Argentinian Navy possessed four diesel electric (DE) submarines, two modern German built Type *209s*, and two older submarines. Of these four boats, only one of the Type *209s* was capable of active patrol during the conflict, the *San Luis* (Wilbur 1996).

The *San Luis*, which "operated 800 nm from its base and made two attacks on British warships . . . demonstrated considerable proficiency . . . when it eluded the best ASW efforts of the Royal Navy, [further,] over 200 items of ASW ordnance were employed against this one submarine, mostly against false contacts" (Challenge 2002). Following the war, it was determined that the torpedoes failed to hit their targets due to faulty fire control maintenance, and the *San Luis*' commander related:

> There was no effective counterattack. I don't think they knew we were there until they heard our torpedoes running, and then the erratic nature of those weapons' behavior apparently prevented them from tracing the torpedoes back to our position. We were *never* under direct attack (Wilbur 1996).

From the attempts to hunt this one submarine, it can be seen that fighting conventional submarines in littoral environments can be a time-consuming and expensive undertaking.

STATE OF AIP SYSTEM IMPLEMENTATIONS

The most common types of proven AIP systems tested or installed in submarines are the following:

- Proton exchange membrane fuel cells
- Stirling cycle engines
- Rankine cycle power plants
- Closed cycle engines

A PEMFC AIP system is fitted in the *212* class of submarines that German shipbuilders Howaldtswerke-Deutsche Werft GmbH (HDW) and Thyssen Nordseewerke GmbH (TNSW) designed and built. The first German *212* was commissioned in 2005, with three others being commissioned by 2007. The Italian Navy also commissioned two of these submarines, in 2006 and 2007. The propulsion plant of the *212* combines a conventional system consisting of a diesel engine and a lead acid battery, with the PEMFC AIP system used for slow, silent cruising. The AIP system consists of PEMFCs, providing between 30 and 50 kW each. The oxidant is liquid oxygen, and the fuel is hydrogen, which is stored in metal hydride cylinders outside the pressure hull.

An AIP module is also available for retrofit to HDW's existing *209* class submarines. A *209* submarine can be lengthened by the addition of a 6-m hull section, aft of the bridge fin. The fuel cell system would consist of two 120 kW fuel cell modules, a liquid oxygen tank placed inside the pressure hull, and all the necessary pipes and electrical equipment. The hydrogen is stored in metal hydride outside the pressure hull (Psoma and Sattler 2002). With the addition of the AIP system, the submerged endurance of the *209* will be increased by approximately a factor of five, as compared with the baseline DE version.

HDW's latest design, the *214*, combines the strong points of the proven *209* with the advanced technology of *212*. The Hellenic Navy has postponed delivery of their *214*. The South Korean Navy has commissioned two *214* submarines, which are fitted with an AIP system consisting of two Siemens PEMFC modules that produce about 120 kW each. The submarine has an underwater air independent endurance of approximately 2 weeks.

In addition to fuel cells, some submarine producers have invested in Stirling engine technology. Stirling engines are energy conversion devices that operate over a closed, regenerative thermodynamic cycle. The power pistons operate in a closed helium (or hydrogen) working gas system and heat is continuously transferred to the cycle via a heat exchanger. As the combustion chamber is external and separated from the working gas, it is possible to select the pressure of the combustion chamber (Hellqvist 1993). A relatively high combustion pressure allows the exhaust products to be discharged overboard at depth through a special mixing unit, where the carbon dioxide is dissolved in the seawater cooling system. The Swedish company Kockums has its own Stirling system, which has been installed on the submarines *Nacken* and *Gotland*, and it is also available as a retrofit to different submarine types. Kockums has produced three submarines of the *Gotland* class, with the first entering commission in 1996. *Gotland* is equipped with two MTU diesel engines, and two Kockums Stirling AIP units, which provide up to 75 kW each (SSK *Gotland* 2003), and provide an air independent endurance of 2 weeks. The oxidant of the AIP system is liquid oxygen, which is stored inside the pressure hull, and the fuel is diesel fuel.

The Module Energie Sous-Marin Autonome (MESMA) system is the AIP system that Direction des Construction Navales (DCN) of France developed, mainly for export purposes. The operation of the system is based on a closed Rankine cycle engine. Liquid oxygen stored at $-185\,^{\circ}C$ is pumped into a vaporizer, where it becomes gaseous. It is then led into the combustion chamber, where it mixes with ethanol and produces a thermal output of $700\,^{\circ}C$, at a pressure of 60 bar, to heat the secondary cycle. The high pressure of the exhaust gases allows for operation of the system at any diving depth without the need for additional equipment. The secondary circuit is a steam-driven Rankine cycle turbine, which drives a high-speed generator. The two designs of DCN that are fitted with the MESMA AIP system are the *Scorpene* and the *Agosta*.

The propulsion system of *Scorpene* is different in the two existing variants (SSK *Scorpene* 2003). The newest variant, the AM-2000, is equipped with a MESMA AIP system. *Agosta* submarines are currently in service in the French, Spanish, and Pakistani Navies. The first of the improved versions of the submarine, the *Agosta 90B*, was delivered to the Pakistani Navy in 1999, although without the AIP propulsion capability. The PNS Hamza *Agosta 90B* submarine, fitted with a MESMA AIP system, completed customer acceptance trials in September 2008. The MESMA will also be retrofitted to their first two submarines (Deagal 2008).

DESIGN CONSIDERATIONS

The performance factors of the AIP system that affect the vulnerability of the submarine are the AIP endurance and the balance speed. AIP endurance is the period of time that a submarine can remain submerged without the need to use its diesel engines in order to charge the batteries. Balance speed is the speed at which the maximum AIP power is equal to the submarine power requirements for hotel load and propulsion. Above the balance speed, it is effective to run both the AIP system and the storage battery, because a lightly loaded battery has a larger effective capacity. Typical advertised values of AIP endurance for some modern submarines are 12–14 days at a balance speed of 4–6 knots.

The underwater endurance that any AIP system can provide is limited by the fuel and oxidant carried on-board. The available power of the AIP system limits the maximum underwater speed of a submarine extracting energy only from the AIP system. The power required for high speeds can be extracted only by the storage battery, which also satisfies the underwater power requirements after the AIP fuel and oxidant have been consumed.

A current constraint on submarine design is battery endurance; however, new battery technologies showing considerable advantages in nonmarine industries will enter the marine market soon. After scaling these up to the sizes needed for conventional submarines, significant improvement in the submarine operating profile could be achieved. Higher energy densities and specific energies introduced by advanced technology batteries could translate into longer submerged times and increased submerged speeds.

Design

BASELINE DESIGN SELECTION

A baseline submarine model (a conventional AIP) is developed to serve as a departure point for some design variation studies. The baseline submarine was modeled with the use of a mathematical model developed for this study; therefore, the performance of the submarine is based on estimates and is not intended to accurately model, or to be representative of, any actual existing design. The comparison of the baseline and target performance requirements is presented in **Table 1**.

SYNTHESIS MODEL

In order to apply the method, a synthesis model must be used. The characteristics that the synthesis model should have are the following (Kirby and Mavris 2001):

- It must have parametric inputs, in order to facilitate the use of response surface methods.
- It should be physics based, in order to be able to analyze the impact of the new technologies. A model based on regression analysis of previous designs will not be able to capture the impact of new technologies.
- It needs to include disciplinary technical metric impact factors, in order to simulate the impact of the new technologies. These factors will be referred to as k-factors, and it should be easy for the user to change their value.
- The responses should be quantifiable, in order to relate the responses to the variation of inputs.

TABLE 1: Baseline and Target Submarine Requirements

	Baseline	Target
AIP endurance (days)	14	17
Balance speed (knots)	4	5.5
IR at 8 knots (with AIP) (%)	10	8
OMOE	0.47	0.49

The mathematical model for this study was developed using the software program MathCAD by MathSoft. Using this software package, the designer directly inputs the mathematical equations into the document. The ease of use and the ability to quickly change the equations are the advantages of using MathCAD.

The concept exploration is the part of the design process where the designer specifies the main characteristics of the product. The objective of the concept design phase is to determine the size, weight, and geometric configuration within which the detailed studies can take place (Burcher and Rydill 1994). To achieve a design solution, an iterative procedure needs to be applied, which starts with the definition of requirements.

With the requirements stated, the process of determining the characteristics of the submarine can begin. The flowchart of the model is presented in **Figure 1**.

For conventional submarines, the volume occupied by the payload is approximately 30% of the total pressure hull volume (Burcher and Rydill 1994). Based on this payload volume requirement, a preliminary estimate of the pressure hull volume can be made and the envelope volume can be calculated. Next, the shape and dimensions of the submarine can be iterated to design a hull with the required envelope volume.

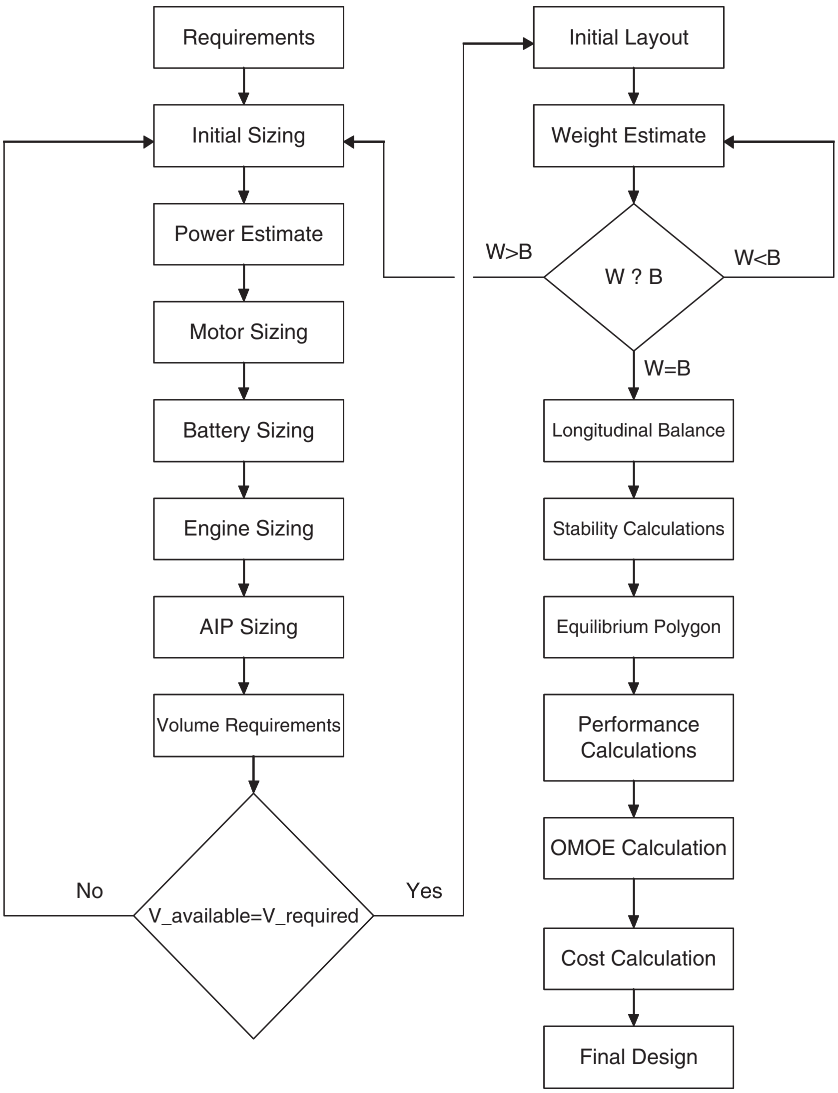


Figure 1: *Design Flowchart (Based on Burcher and Rydill 1994)*

The selected shape and dimensions provide the ability to calculate the wetted surface and the resistance of the submarine. Based on this preliminary estimate of the resistance, the propulsion motor can be sized to meet the speed requirements. After specifying the required power at different speeds, the battery size can be determined based on the required underwater endurance at loiter speed or the required time that the submarine needs to sustain the maximum speed.

The sizing of the diesel generator plant is based on the submarine's desired operational profile during snorkeling operations. The limiting factor for the power of the diesel engines is the maximum current limitation on charging the batteries. Having determined the power of the engines, and knowing the required endurance, the necessary amount of fuel can be calculated.

In addition to designing a DE submarine, the model developed for this study has the ability to design a "hybrid" submarine, which retains the DE capability and adds an AIP system. In the case of the "hybrid" submarine, the size of the AIP system and the necessary amount of fuel and oxidant are based on the required balance speed and underwater endurance.

Based on the size estimates of the individual components presented above, a preliminary required size of the pressure hull is determined. This volume is fed back to the beginning of the model, and a new iteration of the above calculations begins, leading to a new pressure hull volume, new dimensions, new power requirements, and new sizes for the pressure hull components will be calculated. The iterative process of the volume balance stops when the difference between the required and the available volume of the pressure hull is $<1\%$.

The weights and centers of gravity of the submarine's systems are derived from the physical dimensions of the equipment or from regression equations. For every submarine, a balance between weight and buoyancy is necessary; however, there are many ways to achieve balance. In this model, the displacement that corresponds to the everbuoyant volume is compared with the surfaced displacement of the submarine. Everbuoyant volume is the sum of the pressure hull and the volume of outboard items.

In the case that the everbuoyant volume is less than the total weight of the submarine, the submarine is a weight-limited design. Because of uncertainty in the conceptual design stage, the designer does not generally have the luxury of saving weight. For small adjustments, some of the lead ballast can be removed; however, the fraction of lead to the normal surfaced displacement should not be reduced below 5%. If greater adjustment is necessary, buoyancy must be added by increasing the length over diameter ratio, which adds length to the parallel mid-body of the submarine. Then, the iterative process of volume balancing should start again.

In the case that the everbuoyant volume is greater than the total weight of the submarine, the submarine is a volume-limited design. Because of the uncertainty at this level of design, the volume requirement cannot be reduced. Therefore, fixed ballast must be added in order to balance buoyancy and weight.

In both the weight-limited and the volume-limited case, weight balance is assumed when the difference of the displacement that corresponds to the everbuoyant volume with the surfaced displacement of the submarine is $<1\%$.

Having obtained the volume and weight balance of the design, the longitudinal balance must be obtained. The longitudinal center of gravity of the submerged submarine is required to be at the same vertical plane as the center of buoyancy. The center of buoyancy is calculated based on the geometric shape of the submarine, and the center of gravity is estimated from the centers of gravity of the individual weight groups. In addition to the requirement for submerged longitudinal balance, the submarine must be balanced in the surfaced condition as well. The longitudinal location of the center of gravity must be in the same vertical plane as the surfaced center of buoyancy. This can be achieved by proper placement of the ballast tanks. In order to ensure that the center of gravity is in the same vertical plane as the surfaced and submerged center of buoyancy, it may be necessary to adjust the location of the submarine's center of gravity. This can be done by adjusting the longitudinal location of the lead ballast.

Submerged transverse stability requires that the center of gravity be below the center of buoyancy. The magnitude of their distance determines the restoring moment of the submarine. The vertical location of the lead ballast's center of gravity is iterated until the vertical distance between the center of gravity and the center of buoyancy of the submarine is at least 1 ft.

In addition to stability and longitudinal balance requirements, the submarine should be able to maintain neutral buoyancy and level trim under all conditions. Any loading condition must be able to be compensated by the trim and compensating system. In order to ensure that the submarine can operate under all loading conditions, the equilibrium polygon must be checked. If any loading conditions fall outside the enclosure of the polygon, the submarine cannot be properly ballasted with the use of the trim and compensating system. Therefore, the system must be resized or the fixed ballast must be rearranged.

Having achieved a balanced design, the model estimates the performance parameters to ensure that it achieves the owner requirements. The performance module calculates the maximum surfaced range, the maximum submerged range at different speeds of advance (SOA), and the IRs that correspond to those speeds. It also calculates the overall measure of effectiveness (OMOE) of the design, based on the relative weights that can be specified by the user.

Technology Performance Assessment

With a basic understanding of the state of the technology, the performance of these boats is investigated. This analysis is conducted using notional conventional DE and AIP submarines, as well as a future concept AIP submarine, as synthesized using the process described in the previous section.

The next step in the process of quantifying performance is to develop a notional scenario in which the submarine can be evaluated.

NOTIONAL SCENARIO

The notional scenario proposed for this evaluation is a patrol of 21 days' duration. It will be composed of three transit periods and two patrol periods in different areas. **Table 2** contains the details of the speed, time, and distance for each of the five legs of this patrol.

For simplicity, it will be assumed that the submarines operate at constant speeds during each leg of the patrol.

The notional submarines receive orders to transit to Patrol Area 1 at a speed of 8 knots, patrol there for 14 days at a speed of 5.5 knots, transit to Patrol Area 2 at a speed of 5.5 knots, patrol there for 2 days at a speed of 5.5 knots, and finally transit back to base at a speed of 8 knots.

TABLE 2: Timeline of the Notional Patrol Scenario

Leg	Speed (knots)	Time (days)	Distance (nm)
Transit 1	8	2	384
Patrol 1	5.5	14	1,848
Transit 2	5.5	1	132
Patrol 2	5.5	2	264
Transit 3	8	2	384
Total		21	3,012

The current AIP submarine will use its battery for Transit 1, and its AIP system while in Patrol Area 1. At the end of this time, it will have run out of AIP fuel and oxidant. It will then transit to Patrol Area 2 and patrol there as a DE submarine and will return to port on battery.

The future concept will transit using its battery to the first patrol area, and then use the AIP system to patrol at Area 1. After that, it will transit to Patrol Area 2 using the AIP system. It will then conduct Patrol 2 using only the AIP system and will start its transit back using its batteries. The methods of propulsion for each submarine are summarized in **Table 3**.

Figure 2 provides a graphical description of the notional patrol scenario.

This scenario is chosen because the total endurance is realistic, and can easily demonstrate differences between the notional submarines.

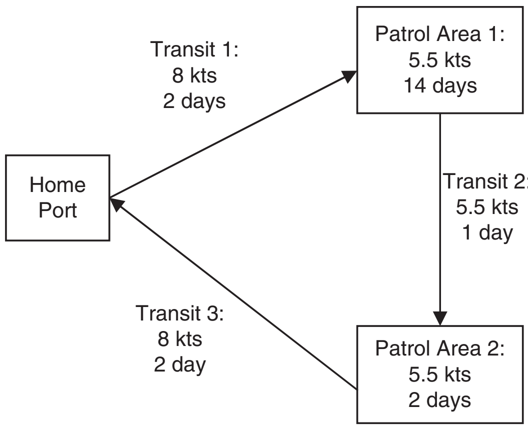
NOTIONAL PERFORMANCE PARAMETERS

To quantify the performance of these submarines, it must be understood that there are

TABLE 3: Summary of Propulsion Use

	Propulsion Source Used	
Leg	Conventional AIP	Future Concept
Transit 1	Battery/DE	Battery/DE
Patrol 1	AIP/Battery/DE	AIP
Transit 2	Battery/DE	AIP
Patrol 2	Battery/DE	AIP
Transit 3	Battery/DE	Battery/DE

Figure 2: *Graphical Description of Notional Patrol*



many variables and situations that can be examined to determine the effectiveness of current technology.

The selection between different designs can be conducted using an OMOE and a structured analysis and multicriteria decision-making process. Such a process and its corresponding analysis must be firmly grounded in the principles of systems engineering and it must have clear traceability back to the requirements that were established (Hootman and Whitcomb 2005).

Specifically, a structured, hierarchical effectiveness and performance analysis can facilitate an informed negotiation of requirements, desirements, and design parameters by decision makers. This process allows vehicle design and mission requirements, "when optimized to maximize the overall effectiveness of the system, [to] become the requirements to which the vehicles are then designed" (Soban and Mavris 2000). This can be further generalized to the whole concept design framework to show that the objective is not to develop a single absolute optimum, but rather to elicit relationships for determining what characteristics have the greatest impact on the design, why they do, and how these relationships can be better exploited to lead to a better design.

The first step of the process is the definition of the requirements. The "owner" specifies a range of acceptable values, from a "goal" or an optimum value for that characteristic to a "threshold" or a minimum acceptable value. A ship that does not meet at least the "threshold" values specified by the owner is considered an unacceptable design.

All platforms have to meet the threshold level as a minimum requirement. Then, using a linear scale, the performance of the platform with respect to a specific Level II system parameter is scored between 0 and 1. Attaining the threshold assigns a 0 to the platform, while attaining the goal assigns a 1. Departing from current technology, **Table 4** shows the ranges of performance assessment parameters that will be considered.

The numerical output of the performance module is the mission OMOE. The levels of performance are compared with the Level II (measures of performance) goals and thresholds, and a score between 0 and 1 is assigned to each parameter. The scores for each Level II parameter are combined and multiplied by the weights

TABLE 4: Performance Assessment Parameters

Level I	Level II	Threshold	Goal
Mobility	Maximum submerged speed (knots)	15	25
	Days of stores	30	90
	Time at maximum speed	0.5	2
	AIP balance speed (knots)	2	8
Endurance	AIP endurance	5	25
	Maximum submerged range (nm)	2,000	10,000
	Maximum surfaced range (nm)	4,000	14,000
Mission capability	Number of torpedo tubes	6	10
	Total number of weapons	10	25

of the associated Level I (measures of effectiveness) parameters. The mission OMOE is then the sum of the Level I scores. Because of a lack of actual stakeholder preference information, alternatives at each level are weighted equally, although the model is easily implemented with different weightings to be able to model varying customer preferences.

For this study, an incremental increase in capability was chosen for the future submarine.

- Increase the AIP endurance: AIP endurance is the period of time that a submarine can remain submerged without the need to use its diesel engines to charge batteries during snorkeling operations. The typical advertised values for the AIP endurance of some of the modern submarines are 12–14. Extended AIP endurance reduces the time that the submarine needs to spend snorkeling.
- Increase the balance speed: As explained above, balance speed is the speed at which both the hotel and the propulsion power requirements of the submarine are satisfied by the AIP system. Hence, balance speed reflects the available power by the AIP system. At speeds higher than the balance speed, the power requirements of the submarine can be satisfied by a combination of the battery and the AIP system. A lightly loaded battery has a higher effective capacity; therefore, the time that the submarine will have to break the surface in order to charge its batteries will be reduced and the exposure of the submarine to any threats will also be reduced. The exposure of the submarine can be quantified by the indiscretion ratio (IR).
- Decrease the IR: IR is the fraction of the time that the submarine spends snorkeling, and can be calculated by IR equation

$$IR = \frac{t_{\text{snorkeling}}}{t_{\text{snorkeling}} + t_{\text{quiet}}} \tag{1}$$

  where $t_{\text{snorkeling}}$ is the time that the submarine spends snorkeling to recharge the battery and t_{quiet} is the time that the submarine spends loitering using the battery or the AIP system for the hotel and propulsion loads. Reductions in the indiscretion rate make the submarine less vulnerable.
- Increase the OMOE.

These target requirements are summarized in **Table 5**.

Analysis

Now that a set of notional requirements to fit the future mission has been developed, it is appropriate to compare the capabilities of current and proposed submarines.

Using a mathematical model developed for this study, the underwater range, underwater endurance, and the IR were estimated as a function of speed for notional submarines using three different propulsion systems:

- A DE
- A "hybrid," which has DE and AIP capability
- A future concept based on the target requirements of Table 5.

The submerged displacement of the baseline submarine is 1,480 tons, and it has a 163 kW AIP system. **Figure 3** shows the comparison of the underwater endurance (in hours) as a function of speed.

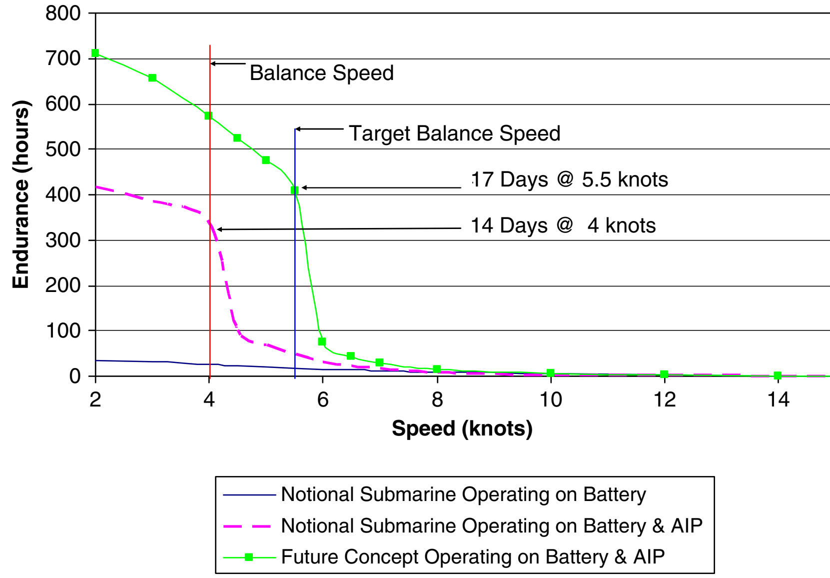
The discharge fraction used in the calculations of battery endurance was 30%. It is clear that for speeds above the balance speed, the endurance decreases rapidly.

Closely related to endurance is a submarine's range. The typical "advertised" submerged endurance for some of the modern AIP submarines is 12–14 days. The notional baseline AIP submarine has an AIP endurance of 14 days at 4

TABLE 5: Target Requirements

AIP endurance	17 Days
Balance speed	5.5 knots
IR at 8 knots (with AIP)	8%
OMOE	0.49

Figure 3: *Endurance as a Function of Speed*

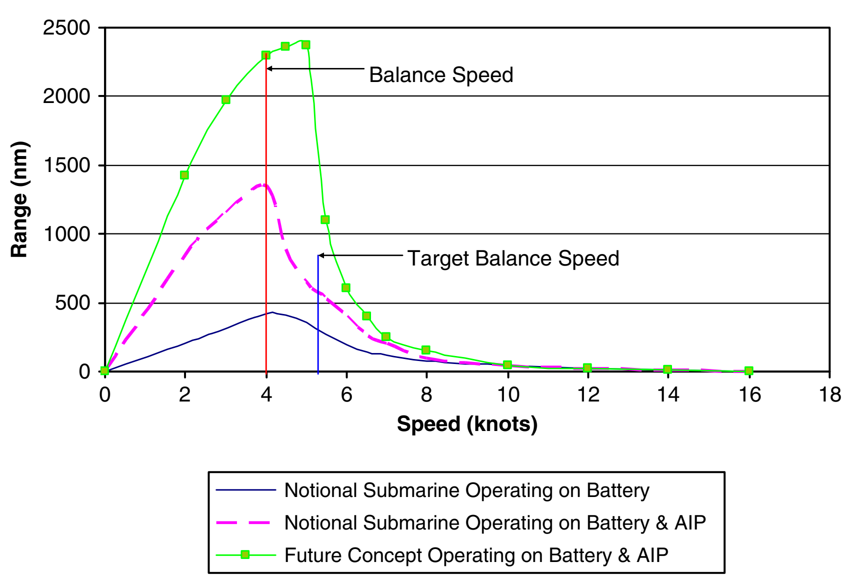


knots and a maximum underwater range of 1,344 nm as shown in **Figure 4**.

The maximum underwater range of the submarine operating solely on battery is 420 nm, and the future concept has an AIP endurance of 17 days at 5.5 knots and a maximum underwater range of 2,370 nm. These results demonstrate that an AIP submarine can remain submerged for much longer than a DE submarine, as well as the room for improvement in AIP technology.

Another analysis to verify the advantages of the AIP submarine is to examine the IR. The IR is the fraction of the time that the submarine spends snorkeling, and thus more exposed to the enemy. Because of restrictions in battery and air quality endurance, DEs must rise to the surface to run their diesel engines to recharge their batteries and circulate fresh air while either surfaced or snorkeling. During this process, the DE must break the surface of the water, exposing itself to detection. The AIP submarine does not have to do this as often, as shown in **Figure 5**.

Figure 4: *Range as a Function of Speed*



From this figure, it is clear that the IR increases quickly, even at slow speeds. If the DE boat is operating at 4 knots, its rate is around 6.5%, while the AIP submarine has an IR of 0.

Next, the boat's probability of detection is examined. This metric must relate the patrolling submarine to a platform and sensor searching for it. Because this situation has a moving searcher seeking a moving target, a "perfect" search, in which the target is stationary, should not be used. Therefore, the primary tool for conducting this analysis will be a "random" search. A "random" search is clearly not the best way to conduct a deliberate search; however, it is generally considered to be a good lower bound for detection probability, and "often provides accurate answers" (Washburn 1996).

In this application of a random acoustic search, the sensor performing the search will be treated as a "cookie cutter," that is, the sensor will sweep out a path at a given speed and for a given time with a width twice the range of the sensor. The range of the sensor is considered to be a "positive detection range," so that if a target is outside the range, it will not be detected, and if it comes within that range, it will be detected. For the purposes of this study, a "positive detection swath" (PDS) variable is created, which is a weighted average of snorkel and battery (or AIP) operation detection distances based on the submarine's IR.

Given this notional patrol scenario, the five stages of the patrol will be analyzed individually. The random search formula used to conduct the surface search is given by random search equation

$$P_{\text{detect}} = 1 - e^{\left(\frac{-24 N_S V 2D_{\text{patrol}} t}{A}\right)} \qquad (2)$$

where A is the search area in nautical miles, $2D_{\text{patrol}}$ is the PDS, N_S is the number of searchers, V is the search speed in knots, and t is the time in days. To simplify this analysis and show the difference in IR, one of the most important

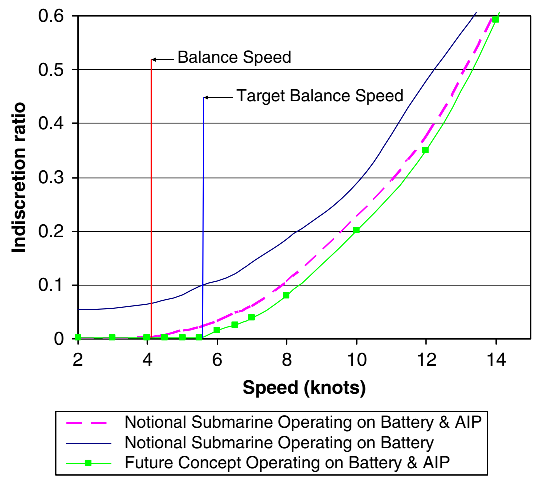


Figure 5: *Indiscretion Rate as a Function of Speed*

MOPs, between the DE and AIP boats, many of these variables will be held constant.

One of the most influential factors in any search is the amount of area that must be searched. It is assumed that the minimum amount of ocean area that this notional patrol could cover is approximately 110,000 nm^2. Therefore, A will be held at this value. Further, N_S will be held at three searching platforms at a V of 10 knots. This leaves the PDS as the only variable that will be changed.

As mentioned earlier, the PDS is a weighted average of detection distances using the IR. This simplifies the analysis and clearly demonstrates the impact of indiscretion rate. It is important to stress that these are rough order of magnitude estimates based on simplified data. Many technical factors, ranging from environmental to design and operational, impact this analysis and are not being considered in order to simplify the calculations.

Given this information and the IRs discussed earlier in the paper, PDS values were determined and probabilities of detection were calculated for each leg of the patrol. The results are presented in **Table 6**.

The higher probabilities of detection during Patrol 1, in comparison with the rest of the

TABLE 6: Summary of PDS Values and Probabilities of Detection

	Battery and AIP		Future Concept	
Event	PDS (nm)	P_{detect} (%)	PDS (nm)	P_{detect} (%)
Transit 1	11.4	14	11.4	14
Patrol 1	6.2	43	5.6	40
Transit 2	6.2	4	5.6	4
Patrol 2	6.2	8	5.6	7
Transit 3	11.4	14	11.4	14

scenario, are a function of the time spent on station. It should be noted that the differences between the submarines are constrained by the manner in which they have been designed in this study. This study investigates potential improvements by varying systems within the same hull. Improved capability is possible with different hull designs. The results demonstrate the probability of detections possible with AIP propulsion.

Conclusions

This paper has refreshed the topic of conventional submarine design, provided examples of analyses that demonstrate the assessment of performance characteristics of current technology, and provided aids for decision makers in determining the impacts of future designs and possible threats.

At the theater level, a technological impact assessment of the operational characteristics of a notional AIP system submarine design was performed using a mission simulation context.

Acknowledgments

This work was performed at the Massachusetts Institute of Technology, Cambridge, Massachusetts. The authors would like to thank the Office of Naval Research for their support through grant number N0001402WR20414.

References

Burcher, R. and L. Rydill, *Concepts in submarine design*, Cambridge University Press, Cambridge, United Kingdom, 1994.

"Challenge of ASW in the Littorals, *The Surface Warfare*." Available at http://surfacewarfare.nswc.navy.mil/magazine/aswsepoct.html, accessed March 2002.

Deagal.com. Available at http://www.deagel.com/news/Pakistan-Receives-Third-Agosta-90B-Submarine-Equipped-with-MESMA-Air-Independent-Propulsion-System_n000005057.aspx, 2008.

Hellqvist, K., "Submarines with air independent propulsion," RINA Warship 93, Naval Submarines 4, 1993.

Hootman, J. and C. Whitcomb, "A military effectiveness analysis and decision making framework for naval ship design and acquisition," *Naval Engineers Journal*, Vol. 117, No. 3, pp. 43–61, 2005.

Kirby, M.R. and D.N. Mavris, "A technique for selecting emerging technologies for a fleet of commercial aircraft to maximize R&D investment," SAE International, 2001.

"Prepared Statement of RADM Michael W. Cramer, Director, Naval Intelligence, Before the Senate Armed Services Committee Seapower Subcommittee," *Federal News Service*, April 8, 1997.

Psoma, A. and G. Sattler, "Fuel cell systems for submarines: From the first idea to the serial production," *Journal of Power Sources*, Vol. 106, No. 1–2, pp. 381–383, 2002.

Soban, D.S. and D.N. Mavris, "Formulation of a methodology for the probabilistic assessment of system effectiveness," Aerospace Systems Design Laboratory, Georgia Institute of Technology, 2000.

"SSK *Gotland* Class (Type A19) Attack Submarine, Sweden," Available at http://www.naval-technology.com/projects/gotland/index.html, accessed January 2003.

"SSK *Scorpene* Attack Submarine, Chile," Available at http://www.naval-technology.com/projects/scorpene/index.html, accessed January 2003.

Washburn, A.R., *Search and detection*, 3rd ed., Institute for Operations Research and Management Sciences, Hanover, MD, 1996.

Whitcomb, C. and G. McHugh, "Asymetric impacts of evolving SSK technologies on future naval deployments," RINA Warship 99, Naval Submarines 6, 1999.

Wilbur, C.H., *Remember the San Luis!*, Naval Institute Proceedings, June 1996, Naval Institute Press, pp. 86–88, 1996.

Author Biographies

Konstantinos Psallidas is a Lieutenant of the Hellenic Navy. Currently, he is the manager of the design office of Souda Naval Base. At the *time of this research, he was a graduate student at the Massachusetts Institute of Technology.*

Clifford Whitcomb, Ph.D., CSEP, is Professor and Chair of the Systems Engineering department at the Naval Postgraduate School, Monterey, California. Dr. Whitcomb teaches and performs research in the areas of product design and development, ship design, system architecture, systems engineering, multidisciplinary design optimization, and multiple criteria decision making as they apply to product design and development. Previously, he was a professor of naval architecture and marine engineering, and the Northrop Grumman Ship Systems Endowed Chair in Shipbuilding and Engineering in the School of Naval Architecture and Marine Engineering, and professor of engineering management, at the University of New Orleans, New Orleans, Louisiana. In addition, Dr. Whitcomb was an eminent scientist in naval electric systems at the Naval Surface Warfare Center, Carderock Division (NSWCCD) Philadelphia Detachment. Prior to his position at UNO, he was an associate professor of naval construction and engineering for the MIT 13A (now 2N).

John C. Hootman is the LPD 17 Class Design Integration Manager in the Expeditionary Warfare Ship Division (NAVSEA 05D3), Naval Sea System Command Headquarters, Washington, DC. At the time of this research, he was a graduate student at the Massachusetts Institute of Technology. He is a graduate of Webb Institute and the Massachusetts Institute of Technology.